Capacitance Based Moisture Sensing for Microgravity Plant Modules: Sensor Design and Considerations

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Capacitance Based Moisture Sensing for Microgravity Plant Modules: Sensor Design and Considerations

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Life support systems for growing plants in microgravity should strive for providing optimal growing conditions and increased automation. Accurately tracking soil moisture content can forward both of these aims, so an attempt was made to instrument a microgravity growth module currently in development, the VEGGIE rooting pillow, in order to monitor moisture levels. Two electrode systems for a capacitance-based moisture sensor were tested. Trials with both types of electrodes showed a linear correlation between observed capacitance and water content over certain ranges of moisture within the pillows. Overall, both types of the electrodes and the capacitance-based moisture sensor are promising candidates for tracking water levels for microgravity plant growth systems.

Nomenclature

CBMS	=	capacitance based moisture sensor
g	=	gravity
ISS	=	International Space Station
LED	=	light emitting diode
VEGGIE	=	vegetable production unit
VWC	=	volumetric water content

I. Introduction

It is difficult to imagine a scenario for a long term human presence in space that does not involve the cultivation of plants in either reduced or zero gravity. From food and nutrition to clean air and water, plants can perform several crucial and interlocking roles. In terms of space flight, combined plant-based and physiochemical processes can create a regenerative life support system. Whereas launch mass restrictions have made stowage and periodic resupply the method used in all manned missions to date[1], a hybrid plant-based/physiochemical bioregenerative system becomes feasible and even preferable after a 3-year, six crew-member mission[2]. With regards to permanent, manned installations –whether on the Moon, Mars, or in orbit– the attraction of making them at least partially self-sufficient is obvious. Achieving this goal would require sustainable sources of food, oxygen, and water; again, plant cultivation can play a critical part in supplying all these needs.

Setting aside these long term goals, growing plants on the ISS or future space flights can tangibly improve crew quality of life and nutrition by providing fresh vegetables. One such system currently in development is VEGGIE, a partially collapsible system utilizing LED lighting with a large growing area. Out of several nutrient delivery methods tested for the VEGGIE, the use of "rooting pillows" seemed to provide the best results: in addition to high

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yields, the pillow design provides for containment of water and soil in microgravity, allows for sustained harvests, and is easily disposable[3]. Two primary concerns of the VEGGIE, as with all plant cultivation units for microgravity, are providing optimal growing conditions and increasing the degree to which the system can be automated.

Because both the number of plants one can grow and the resources to grow them are limited, optimizing yields is particularly important in space agriculture. One factor that can significantly affect plant growth is the moisture content of the soil: too high a water content causes hypoxia in the roots and too low a water content will cause stress, wilting or death[1]. Ilieva *et al.* (2007) demonstrated waterlogging plant roots resulted in a 4-fold change in total plant mass[4]. Not only do plants suffer in these extreme scenarios, but any deviation from the optimal soil water content is likely to cause some degree of plant stress, reducing yields. Complicating matters further, this optimal moisture level can vary by plant and soil type, and different soils require different watering regimes to maintain a given moisture level. All this is true for Earth based cultivation. Still, even if the optimal water conditions and watering schedule are known for a plant/medium on Earth, the same may not be optimal in microgravity[5]. Under conditions of microgravity, capillary forces dictate water behavior whereas gravitational forces dominate under 1 g. Thus, water distributes radially around the water source in 0 g rather than pooling at the bottom of the container. In addition, microgravity affects particle rearrangement, hydraulic conductivity, and other soil-water interactions[6, 7]. As Jones and Or (1999) summarized, models designed to describe water/soil interactions under 1 g on Earth cannot be reliably applied to their interactions in microgravity[6].

Given the desirability of controlling soil moisture levels and the difficulty in predicting them, one solution is to develop sensors that can reliably report soil water content in real time. Moisture sensors allow for increased automation; when the sensor detects a deviation from the optimal moisture content, it could automatically adjust the watering input accordingly. With this sort of setup, crew time needed to maintain the plants, a resource at a premium, would be greatly reduced. Several methods for monitoring soil water content have been developed for terrestrial agriculture[8]. One option often employed on Earth but clearly useless in microgravity is gravimetric moisture sensing. Another popular method, time domain reflectometry, is undesirable for space experiments because it uses frequencies that have the potential to interfere with critical spacecraft or station equipment[9]. Therefore, three measuring techniques are left available: the capacitance method, the heat-pulse method, and tensiometers[9]. It was decided to test the feasibility and desirability of monitoring the moisture content of pillows in the VEGGIE system using two different electrode systems with a capacitance type sensor.

II. Materials and Methods

A. Rooting Pillows and Media

All experiments were conducted using "rooting pillows" (Figure 1): 10 x 15 cm anti-electrostatic bags modified so that a centered 7 x 12 cm section of one side was replaced with a Nitex mesh material. After cutting out a centered 5.5 x 10.5 cm section of one side, the mesh piece was positioned inside the bag and fixed to the anti-electrostatic material by heat-sealing. These heat-seals joined the mesh to the both sides of the bag on three sides while the fourth side had a re-sealable mechanism, effectively restricting the cross-sectional area the media could occupy to 6.5 by 12.5 cm.

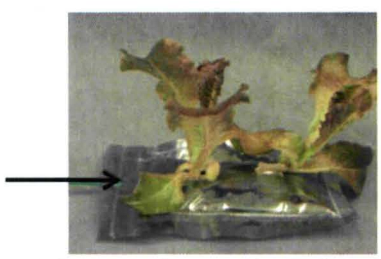


Figure 1. Image of a rooting pillow. *The arrow indicates the perspective taken in subsequent diagrams of the rooting pillows.*

Four different types of soil media were used during the experiments: Arcillite, Fafard, a 70:30 by volume Fafard: Arcillite mixture, and a 50:50 by volume Fafard: Arcillite mixture. Fafard Growing Mixture 2 (Canada) is composed of Canadian Sphagnum peat moss (75%), perlite, vermiculite, starter nutrients, wetting agent, and dolomitic limestone. Arcillite (Buffalo Grove, Illinois) is calcined montmorillonite clay that was sifted to attain a particle size of 1 to 2 mm. To create the mixtures, a one liter graduated cylinder was used to pour each media into a 4 liter container in the proper volumetric proportions. They were then mixed by hand. In some experiments the Arcillite was mixed with 0.75 grams per 100 milliliters of media of Nutricote® (Florikan Corp., Florida), a time-release fertilizer additive; unless noted, the Arcillite had no added Nutricote®.

Moisture content of the media was reported as volumetric moisture content (VWC), which was calculated by dividing the volume of water by the total volume available. For the calibration curve experiments, the volume of the media in the pillow was taken as the total volume. The water retention properties of a soil are described by a soil water curve, which shows the hydraulic potential (suction) needed to achieve a given soil water content (Figure 2).

The lower limit of these curves is the point at which water trapped within the soil particles is the only water remaining in the soil; the upper limit is saturation.

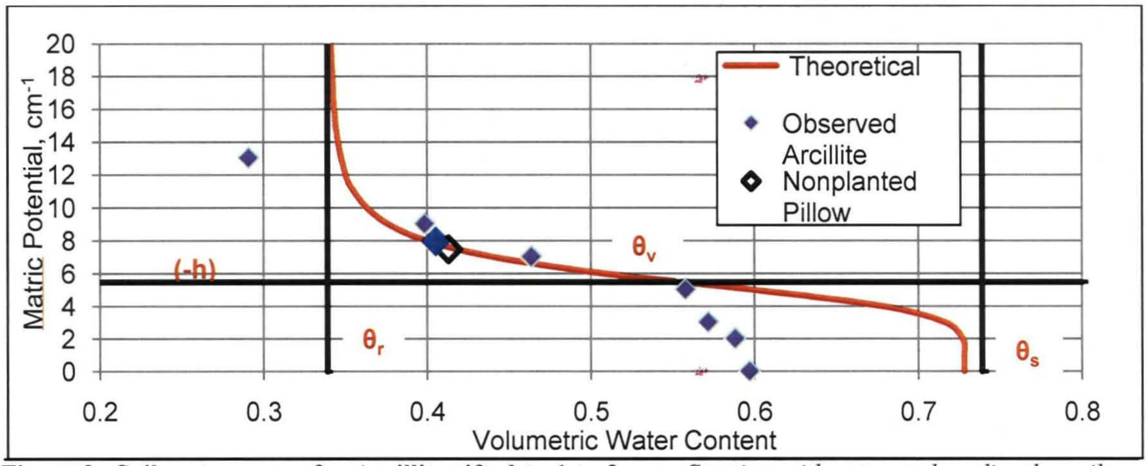


Figure 2. Soil water curve for Arcillite sifted to 1 to 2 mm. *Starting with saturated media, the soil was dried via matric suction until only residual water remains, i.e. water trapped in intra-pores. The difference between theoretical and observed is likely due to differences in packing density or trapped air levels.*

B. Moisture Sensor and Electrodes

The capacitance-based moisture sensor used circuitry described in Nurge and Perusich (2010)[10]. The capacitance across the electrodes was detected by comparison to the reference capacitor, the value being output as a voltage. A datalogger (CR23X Micrologger, Campbell Scientific, Inc.) recorded the output voltage to the hundredth of a millivolt every 5 seconds. During the calibration studies, the capacitance was recorded in 5 second intervals continuously throughout the test. For the long term studies, capacitance was recorded for a period of approximately 10 to 40 minutes for each data point, i.e. each day or half-day for which a value is reported. Although these exact values were recorded in every case, the capacitance values reported below are a "by-eye" to the millivolt approximation of the final stable capacitance value during the recording time, either for a particular day or VWC, judged using a real-time graph of the capacitance output. Time was given to allow redistribution of water to complete.

For any given test, one of two electrode systems was employed (Figure 3). In one system the electrodes were two strips of Mystik (Gurnee, IL) aluminum foil tape. Each strip was approximately 0.9 x 12 cm; for each strip, the last centimeter of the end nearest the re-sealable edge of the pillow was a "tag" (made by folding the tape together) where the alligator clamp lead from the circuit board was attached. While an effort was made to maintain consistent dimensions for these electrodes, they did sometimes vary both between the two strips used in a test and between

Figure 3. Schematic and actual images of two electrode types. *The tab electrode was placed inside the media during trials, as shown in the schematic at right. The aluminum tape strips were placed on the "flaps" of the pillow, depicted as a transparent bar in the diagram at left. The red arrow indicates the perspective taken in the schematic views.*

tests, and this was more than likely a source of error. The second electrode system consisted of the mini-varicon sensor (Lambient Technologies L.L.C., Boston), two fine, interdigitated copper-plated tin electrodes on one surface of a 4 x 2 cm Kapton® piece with two associated leads emerging from one end. This "tab" electrode was protected with single layer of insulating Kapton® tape (Torrance, Califonia); failure to do so caused large capacitance

readings that over-ranged the sensor, possibly due to water causing a short circuit between the leads as they emerged from the electrode. The location and orientation employed with the respective electrode systems is shown in Figure 3.

C. Calibration Curves

All calibration curve tests utilized Arcillite, either 100 mL or 120 mL. This volume was approximated with *dry, loose* Arcillite; no attempt was made to pack it down. Next, the media was poured into the pillow and then the re-sealable side sealed. A dry mass was obtained. Recordings were taken from no water added to saturation (Figure 4).

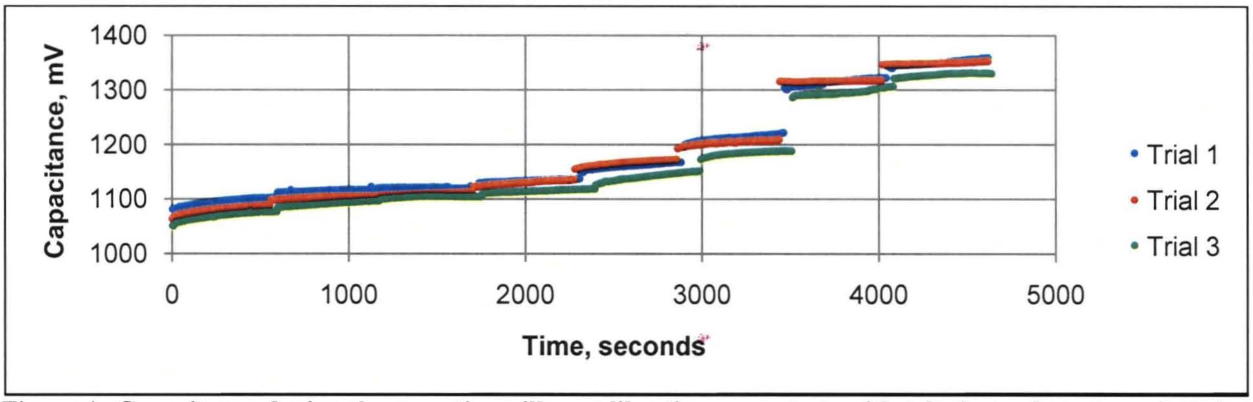


Figure 4. Capacitance during three rooting pillow calibration curve tests with tab electrode system plotted over time. *This graph demonstrates how data was recorded for the calibration experiments; each break and subsequent rise in capacitance indicates a new volumetric water content, VWC, value in the pillow. Note how the capacitance usually levels off to a stable value for each line segment (i.e. VWC level).*

Both the aluminum tape strip electrodes and the tab electrode were tested to determine correlation between VWC and capacitance readings, as well as the range of capacitance values recorded. For the aluminum tape electrodes, electrodes were placed on the rooting pillow as shown above (Figure 3), and the excitatory and receptor leads were connected to the "tags" with alligator clamps. For the tab electrode, once in position the leads from the electrode were joined together with the leads from the circuit board and then covered with electrical tape. Next, with the datalogger recording, known amounts of de-ionized water were added in increments to the media through the Nitex mesh and the capacitance noted as described above.

D. Wheat Growing Experiments

Four rooting pillows -100 mL Fafard, 100 mL of Arcillite with Nutricote ®, 100 mL of the 70:30 mixture, and 100 mL of the 50:50 mixture- were soaked in tap water until fully saturated. Next, two 1 inch slits were cut parallel to each other in the non-mesh sides, and two Nylon wicks were placed in each slit, one wick fully extending to the near outer edge of the pillow and one extending to the midpoint of the pillow. Two Apogee Wheat seeds that had been pre-germinated in a Petri dish for 48 hours were placed in each slit. The pillows were placed mesh side down on a water reservoir covered by a Gortex capillary mat; the Nitex mesh membrane maintained passive hydraulic contact between the media within the rooting pillow and the wet capillary mat (Figure 5).

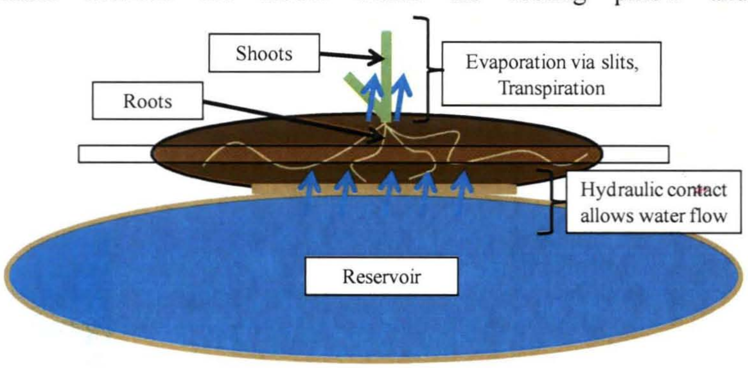


Figure 5. Schematic for passive pillow watering system. *Water is drawn by hydraulic pressure from the reservoir into the media. This system should come to equilibrium, maintaining a constant, soil-dependent volumetric water content inside the pillow.*

The pillows and water reservoir system were placed in a growth chamber at 23°C air temperature, 1200 ppm CO_2, 55% relative humidity, and photosynthetic photon flux of ~300 μmol m^{-2} s^{-1}. After a few days, the healthier seedling

in each slit was left in place while the less healthy seedlings were removed. After 12 days, the pillows were moved to a different growth chamber with 400 ppm CO_2 (approximately the ambient level) instead of 1200 ppm (elevated to increase transpiration). After 25 days, the plants were harvested, fresh mass and height of the shoots determined, and a model for plant growth was made by fitting a sigmoidal curve given the final fresh mass and the number of days since planting. During the 25 days the plants were growing, every 1 to 3 days each pillow was briefly removed from the growth chamber in order to take a capacitance reading.

III. Results

A. Electrode Geometries

Both sensor systems perform satisfactorily as determined by the linearity and range of the response. For the strip sensor from dry to saturated the capacitance reading increased by 200 mV (Figure 6). Additionally, the response was linear in the range from 0.3 to 0.7 volumetric water content. The tab sensor displayed a roughly similar range, but was linear down to approximately 0.2 VWC.

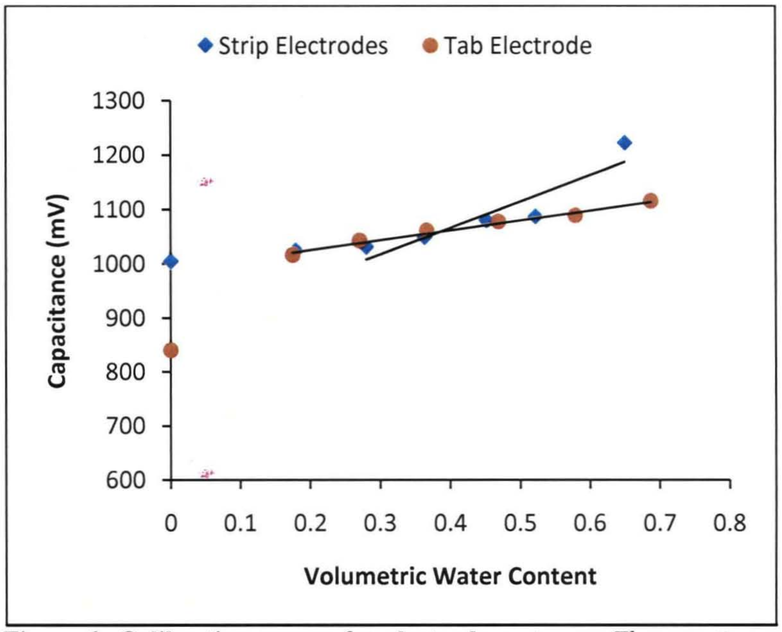


Figure 6. Calibration curves for electrode systems. *The equations and associated R^2 values for the line segments shown are strip electrodes $y = 485.39x + 871.96$ ($R^2 = 0.8528$), tab electrode $y=180.32x+989.91$ ($R^2 = 0.9815$).*

B. Wheat Growing Experiments

Over the course of growing the wheat, the observed VWC stayed constant for the first 9 days, but jumped dramatically at day 10 (Figure 7). This was likely due to fixing the hydraulic contact between the water reservoir sponge and the mesh underside of the pillows; prior to day 10, the capillary mat of the reservoir was bunched and folded in places. Smoothing the capillary mat seems to allow a greater flow of water into the pillows, thus the increase in VWC. From day 10 to 21, the VWC stayed mostly constant except Arcillite, which declined in that period. The second jump in VWC at day 25 could possibly be due to an increased watering regime. Hypothetically, the capacitance sensor should have tracked these changes in VWC, thus graphing VWC versus observed capacitance should be linear for each medium. However, it was found that there is no apparent relationship between capacitance and VWC, especially not a linear increase as was expected

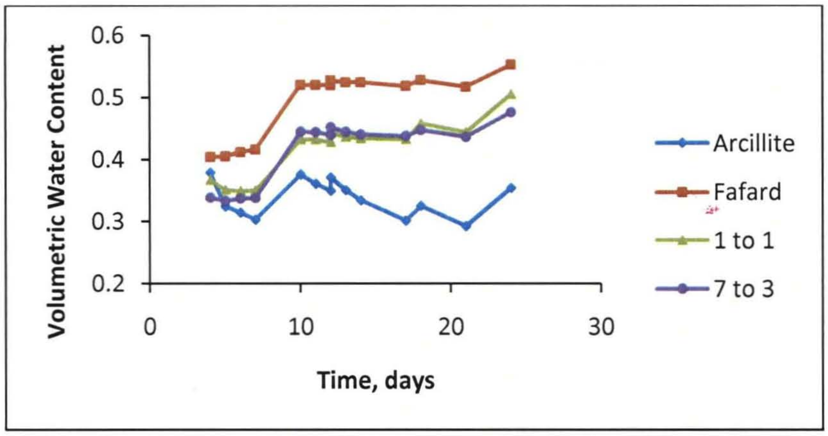
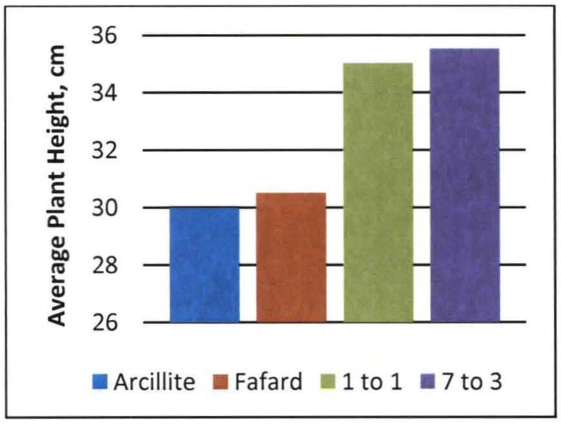


Figure 7. Volumetric water content for four different pillows growing wheat over time. *Each pillow had a different media, listed at right, and each had two apogee wheat plants planted in them at day 0.*

After 25 days, the plants were harvested and their fresh shoot mass and plant heights recorded. As can be seen from Figure 8, the wheat responded differently to different media. It is important to note that since all the media had the thus same passive watering source but different water holding capabilities, each media arrived at a different equilibrium VWC. Previous work has shown Arcillite to have

lower water retention than Fafard. Thus, the pillow with Arcillite had the lowest VWC, Fafard the highest, and the two mixtures somewhere between the two. Arcillite performed the worst in terms of both plant height and shoot mass, and the mixtures performed the best overall.



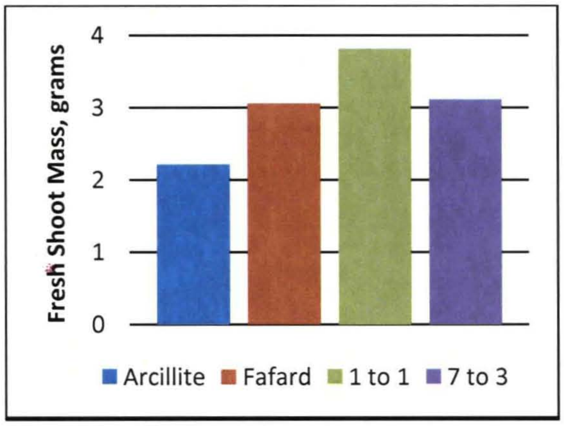


Figure 8. Effect of soil choice on plant height and fresh shoot mass. *Each bar is an average of two plants. Each soil reached a different equilibrium volumetric water content with Arcillite being the driest, Fafard the wettest and the mixtures between those two.*

IV. Discussion

The goal of this study was to instrument the rooting pillow with a CBMS in order to monitor changes in soil water content. The initial testing with calibration curves gives several important observations. First, both types of CBMS electrodes succeed in tracking moisture content, but not without limitations. For the aluminum tape strips a linear correlation between recorded capacitance and VWC was observed. Although volumetric water contents below 0.3 were not read by the strip electrodes, at these VWC levels for Arcillite the water is filling the pores inside the soil particles, the intrapores, not the space between soil particles, the interpores (Figure 2). Because intrapore water is not available to plant roots, no plant could survive long term at or below 0.3 VWC, making this an acceptable lower limit for the electrode. Testing whether this holds for media other than Arcillite, that is, that the sensor not "seeing" intrapore water is the cause for the lower limit is a matter worth looking into.

It is also obvious that the type of electrode plays an important role in determining the response recorded by the CBMS, as the tab electrode had both a different rate of response and the response itself was seen at lower VWC levels. It is tempting to conclude the lower VWC values (0.16) seen by the tab sensor means this sensor is picking up the filling of intrapores (Figure 6). This is possible since the tab electrode is very close proximity with the media, and does not have the barrier of the electrostatic bag material. This could be, but it could also be because of water being trapped between the layer of Kapton ® tape and the electrode, or because (not being a bulk electrode) the area the electrode observes is not uniform but a changing gradient. Regardless, high correlation values between capacitance and VWC demonstrate the tab electrode would be a viable option, though the problems mentioned should be investigated, and the placement of the electrode chosen with care.

One lingering problem for both types of electrodes is the wide variation in the initial offset values. For example, where as strip electrode has an initial capacitance of approximately 1000 mV, tab electrodes start at 830 mV. Part of this variation is likely caused by electrode type; the fact that three repetitions with the tab system had only small differences in initial capacitance values supports this (Figure 4). Additionally, over the course of the tests, it was noticed that the sensor was sensitive to movement of the wires; by the time the tab repeatability trials started the wires were more firmly fixed than for some other tests. Making sure that the apparatus is sufficiently "hardened," as well as additional precautions like using shielded wires to connect to the CBMS circuit, could help lower the observed variations.

Despite these concerns, both electrodes systems along with the CBMS circuit hold promise for accurately tracking the moisture of the rooting pillows with all the advantages that could bring. Several important questions, such as the effects of different media or from sensor placement will allow accurate readings while plants grow in the pillows, are still left to be answered. Still, these results can help guide the investigation into those questions, as well

as advancing towards the goal of effectively instrumenting the rooting pillow to measure moisture in real time, allowing for better plant yields and reduced maintenance.

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